Oral presentation | Data science and AI

Data science and AI-III

Thu. Jul 18, 2024 2:00 PM - 4:00 PM Room C

[11-C-02] Data-driven thermal control of secondary flow in a marginally turbulent square-duct flow and relevance to the invariant solutions

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Keywords: Turbulent square-duct flow , data-driven control, optimization

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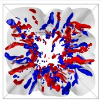
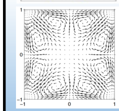
Data-driven thermal control of secondary flow in a marginally turbulent square-duct and relevance to the invariant solutions





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※ Most of computation was performed at "Wisteria" in U. of Tokyo

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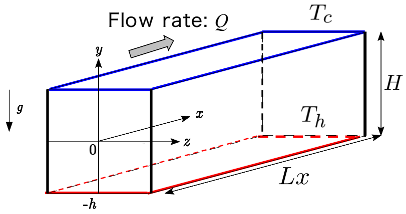
Geometry & simple heating from below



$u_b = \frac{Q}{H^2}$

$\Delta T = T_h - T_c$

$T_0 = \frac{T_h + T_c}{2}$

Governing equation

Ri

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla\left(\frac{p}{\rho}\right) + \frac{1}{Re_H}\nabla^2\boldsymbol{u} + \boxed{\frac{Gr}{Re_H^2}} T^* \boldsymbol{e}_y$$

$$\frac{\partial T^*}{\partial t} + (\boldsymbol{u}\cdot\nabla)T^* = \frac{1}{Pr Re_H}\nabla^2 T^*$$

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Numerical method

- Time: pressure correction fractional-step method
  semi-implicit 3-step Runge-Kutta
  [Verzicco & Orlandi *J. Comput. Phys.* (1996)]
  CFL < 0.3
- Space: Pseudo-spectral method
  streamwise(x), Fourier expansions
  cross-streamwise(y, z), Chebyshev polynomials
  $\Delta x^+ < 16.4 \quad \Delta y^+, \ \Delta z^+ < 5.4$
- 2D Helmholtz equations:
  Chebyshev collocation (fast diagonalization technique) [Haldenwang, *J. Comput. Phys.* (1984)]
  ⇒ "dgemm"×4 → GPU acceleration for high-Re
  but low-Re in my talk, today

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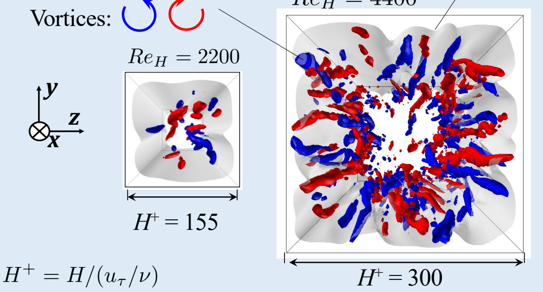
Coherent Structures in a minimal box

$Q = -\Delta p = 0.03 u_\tau^4/\nu^2$

Vortices:



$H^+ = H/(u_\tau/\nu)$

$u_\tau \equiv \sqrt{\frac{\tau_w}{\rho}}$ $\quad \tau_w$: wall shear stress

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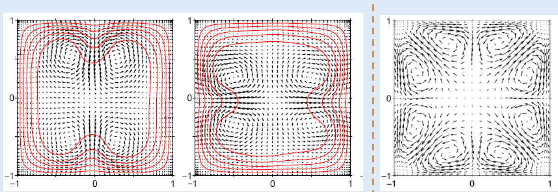
Secondary flows of Prandtl's second kind at marginal-*Re* turbulence $\quad Ri = 0$

$Re_H = 2200$ $\quad Re_H = 4400$



4-vortex

Uhlmann, Pinelli, Kawahara & Sekimoto, *J. Fluid Mech.* (2007)

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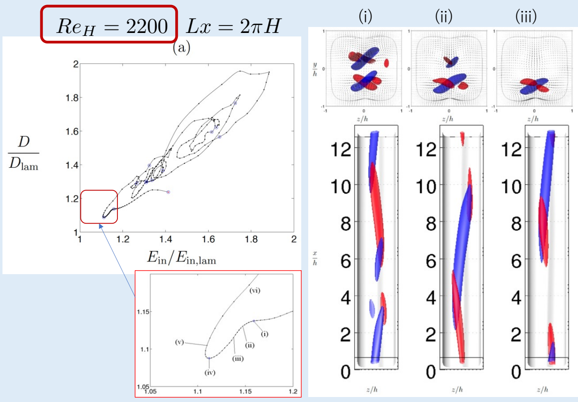
Dissipation vs Energy input $\quad Ri = 0$

$\boxed{Re_H = 2200}$ $\quad Lx = 2\pi H$



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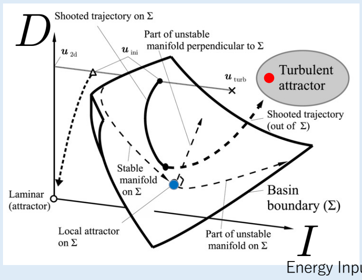
Shooting dynamics in phase space

Energy dissipation



Energy Input

(1) Turbulent flow approaches UPOs or EQs frequently

(2) Then, turbulence represents similar structure with the exact coherent structures

Upper-branch EQ (Active)

Lower-branch EQ (Quiescent)

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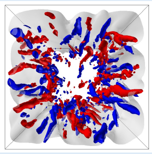
Secondary flow of Prandtl's second kind

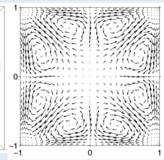
$Re_H = 4400$

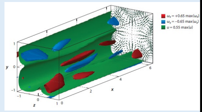
Instantaneous coherent structures

Mean secondary flow

Travelling waves







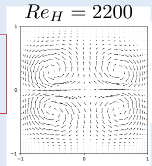
[Pinelli *et al.*, *JFM* (2010)]

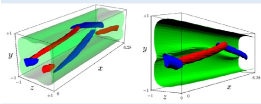
[Uhlmann, Pinelli & Kawahara (*Phys. Fluids*, 2010)]

$Re_H = 2200$

Quiescent turbulence

⇒ Control target (four-vortex state)





[Okino & Nagata (*J. Fluid Mech.* 2010)]

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- Velocity scales
  1. mean bulk velocity: u_b
  2. friction velocity: $u_\tau = \sqrt{\tau_w/\rho}$
  3. buoyancy-induced velocity: $u_g = \sqrt{|g|\beta\Delta T H}$

Friction coefficient $f = 8\left(\frac{u_\tau}{u_b}\right)^2$

- Non-dimensional parameters:

$$Re_H \equiv \frac{u_b H}{\nu},\quad Pr \equiv \frac{\nu}{\kappa},\quad Ri \equiv \frac{|g|\beta\Delta T H}{{u_b}^2} = \frac{Gr}{Re_H^2} = \left(\frac{u_g}{u_b}\right)^2$$

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Previous my works

- Reynolds-number effect [Uhlmann *et al.*, *JFM* (2007)] [Pinelli *et al.*, *JFM* (2010)]
  - 4-vortex state in a iso-thermal square duct $Re_H = 2200 \sim 3000$
  - Puffs in a square duct as in a pipe flow $Re_H = 1800 \sim 2000$
- Richardson-number effect $0 \lesssim Ri \lesssim 1.0 (Re_H = 3000, 4400)$, $Pr = 0.7$
  - Turbulence-driven vs buoyancy-driven

[Sekimoto, Kawahara, Sekiyama *et al.* *PoF* (2011)]
- (Prandtl number effect)

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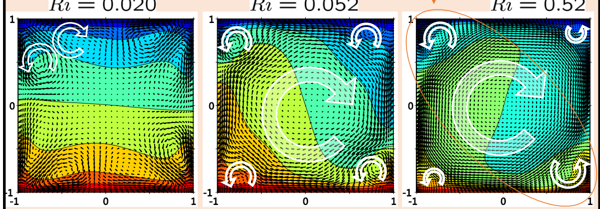
Mean temperature & secondary flow

$Lx = 2\pi H$, $Re_H = 4400$

- Buoyancy effects appear at: $Ri \sim 0.025$
  Buoyancy is dominant at: $Ri > 0.25$

Buoyancy-induced

(I) $Ri = 0.020$ (II) $Ri = 0.052$ (III) $Ri = 0.52$



[Sekimoto *et al.* *PoF* (2011)]

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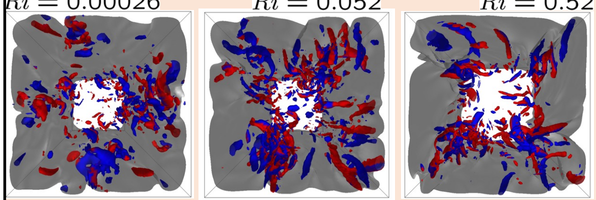
Coherent Structures

$Re_H = 4400$

$u = 0.6u_b$ $Q = -\Delta p = 0.03u_\tau^4/\nu^2$

(I) $Ri = 0.00026$ (II) $Ri = 0.052$ (III) $Ri = 0.52$



[Sekimoto *et al.* *PoF* (2011)]

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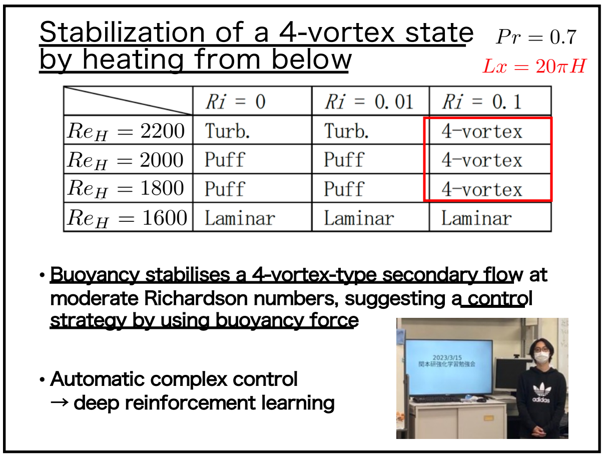

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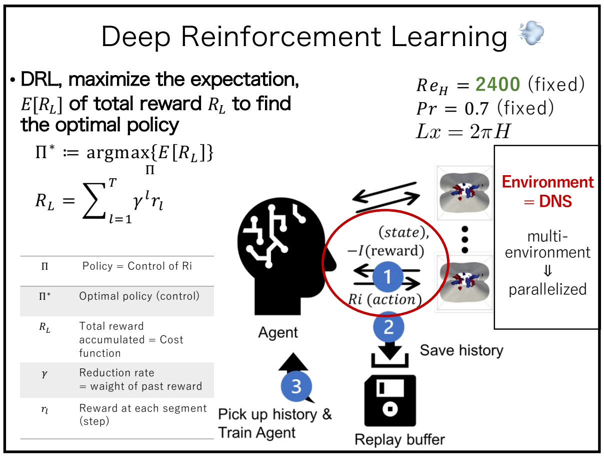

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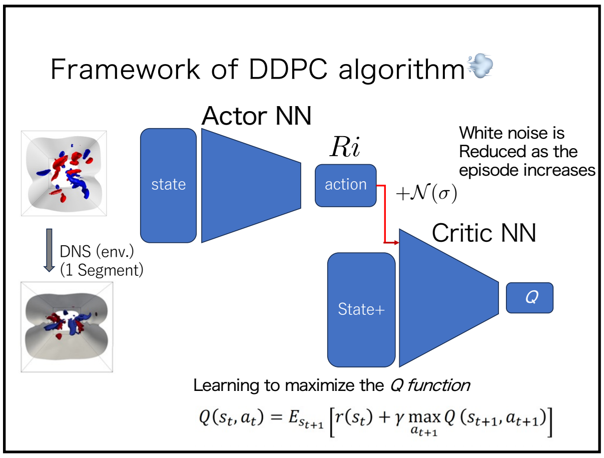

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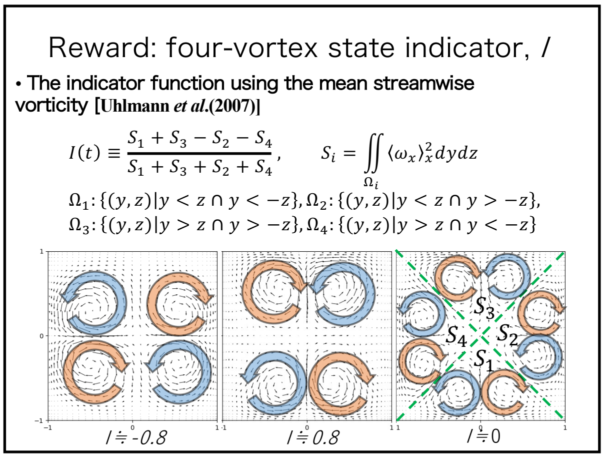

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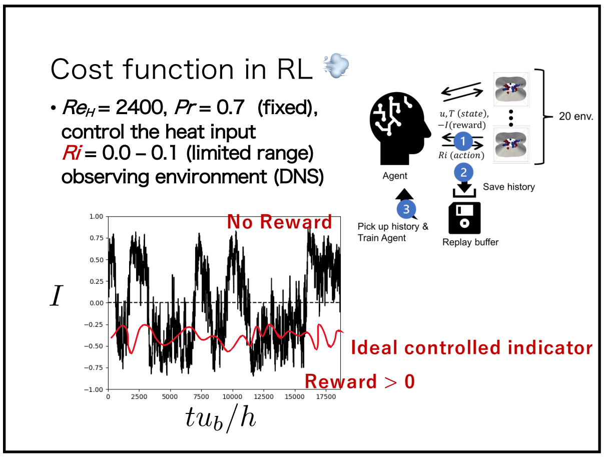

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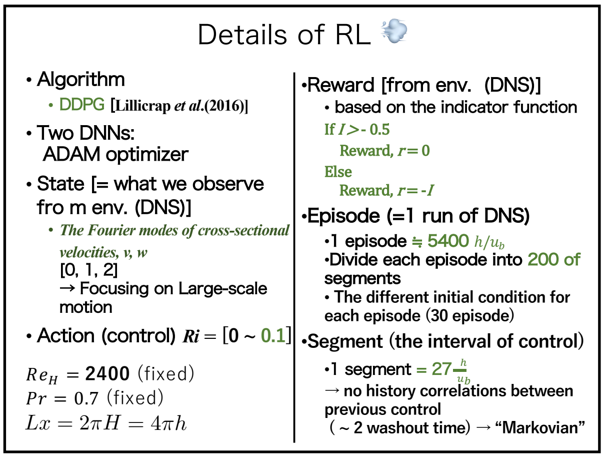

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The structure of Neural Networks

- DDPG has two NN: Actor NN calculates the action from the state, and the Critic NN does Q of actions for each state
- Actor NN
  - state(13068)⇒(32768)⇒(4096)⇒(512)⇒(64)⇒action
- Critic NN
  - state+, action(13069)⇒(32768)⇒(4096)⇒(512)⇒(64)⇒Q-value
- Activation function: ReLU
- Fully-connected

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Hyper parameter for NNs

- Learning rate
  - Actor_lr = 0.0001
  - Critic_lr = 0.001
- Reduction rate (almost no consideration from past rewards)
  - 0.99
- soft update parameter (target NN)
  - 0.005
- Replay buffer
  (common for all episodes and agents, necessary for parallel environments)
  - 2000 buffer (remember the latest 10 episodes)
  - Butch size: 64

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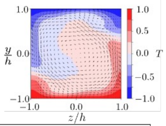
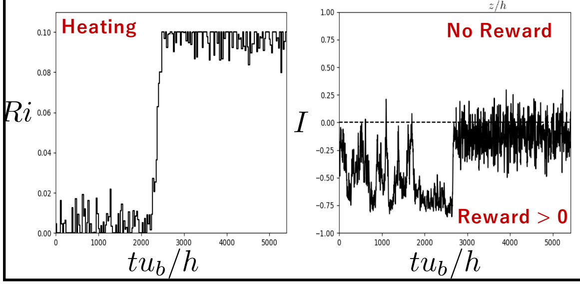
Result: episode1

- Increases $Ri = 0.1$
  - The thermally-driven circulation ⇒ failed





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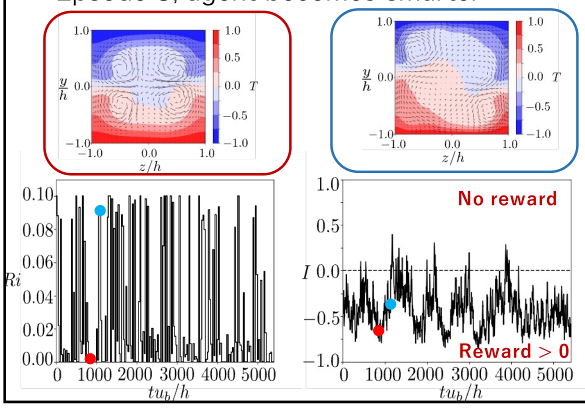
Epsode 3, agent becomes smarter



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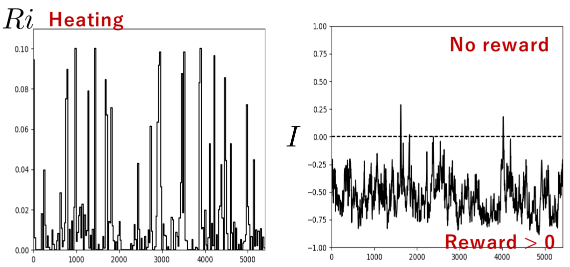
Episode 8

- Switching between $Ri = 0$ and $Ri = 0.1$
  - An intermittent heat control is realized
  - It keeps one on the secondary flow pattern of $I < 0$



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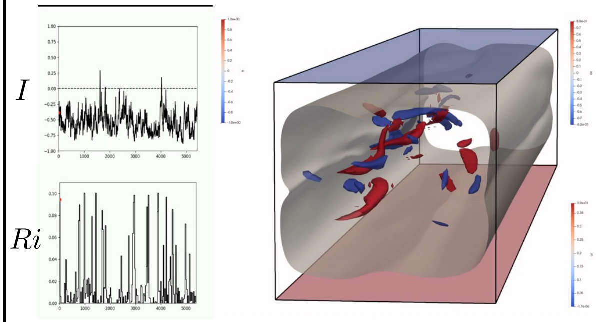
Control: ON (Movie)



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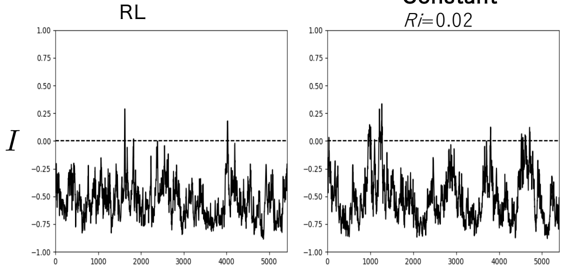
Constant heating (Ri =0.02) vs RL-control [from the same initial condition]

- Dynamic heating controled by RL achieves more-stable four-vortex pattern…

RL

Constant
Ri=0.02



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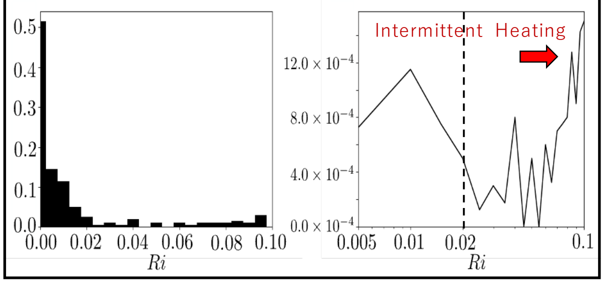
Contribution of intermittent heating

- Ri →probability density function (PDF, left)
  → pre-multiplied Ri, PDF is multiplied by Ri (right)
  - In logarithmic scale in Ri → Area corresponds to the total heat input
  - Compare to the constant heating (Ri = 0.02) → 20% heat reduction



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Summary and perspectives

- Complex 3-D flow with Re-, Ri-, Pe numbers
  - (also aspect ratios, As, Computational domain, Lx, etc.)
  - Stabilized the mean secondary flow pattern, which is called as a corner flow, using buoyancy force
    → heat enhancement, particle migrations (or separations), control in a micro-reaction channel
- Difficulties of flow control from the strong nonlinearity of turbulence
  - Successful nonlinear control method using (deep) reinforce mentlearning
    → now, targeting a specific known flow pattern (4-vortex state)
  - Background physics is important for the further application with ML techniques → AI technology
    → The target flow is realizable? Dynamical system approach of turbulence
    → Which ML models are suitable? How do we reduce the complexity → GPU mem.
    → How about hig-Re？
- High-fidelity CFD are expensive
  - Parameter optimization using Bayes optimization or GA algorithm
  - Keep developing the advanced GPU-accelerated code (or QPU-acceleraged?)
  - Scale up
    → Power-game in industry and international-collaboration in academic

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Thank you very much

Questions and discussions → e-mail: asekimoto@okayama-u.ac.jp
Plese visit: AtsushiSekimotoLab.
(Data-driven computing, dynamical system, flow control)
https://sites.google.com/view/sekimoto-lab/research

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